

# High-Speed Interconnection Characterization using Time Domain Network Analysis

Roger B. Marks, Donald C. DeGroot, and Jeffrey A. Jargon  
National Institute of Standards and Technology  
325 Broadway, Mail Code 813.06  
Boulder, CO 80303  
phone: 303-497-3037  
fax: 303-497-7828  
email: marks@nist.gov

**Abstract**—Time domain network analysis (TDNA) has become a realistic competitor to conventional automatic network analyzers. Off-line processing of data from fast digital sampling oscilloscopes can provide measurements of network parameters with an accuracy that is acceptable for many packaging and interconnection problems at frequencies from dc to over 10 GHz. Since many packaging laboratories have ready access to the required instruments, TDNA brings many advanced measurement capabilities into the hands of engineers to whom a conventional network analyzer is unavailable.

## Introduction

Due to advances in device speeds and packaging density, the electronics packaging industry increasingly encounters requirements for the measurement of network parameters — scattering parameters, impedances, and the like. However, the digital industry has not embraced the sort of microwave instrumentation conventionally used to obtain such measurements. An alternate form of network analysis based on time domain instruments is a better fit to the industry infrastructure and is consequently beginning to make an impact.

Network analyzers, in conjunction with on-wafer probe stations, allow a full and accurate characterization of microelectronic devices, packages, and interconnections in terms of “vector” (that is, complex-valued) network quantities [1]. A conventional implementation, which we call a “frequency-domain network analyzer” (FDNA), uses a swept-frequency source and a set of phase-sensitive receivers. The instrumentation is expensive and typically limited to two test ports. In FDNA, error correction is essential, and automatic, computer-controlled calibration and data processing are recognized as mandatory components of a successful instrument.

In the digital electronics industry, network analyzers are uncommon, but fast digital sampling oscilloscopes are routinely available. Such oscilloscopes offer many possible channels with fast response times. When configured for time-domain reflection/transmission (TDR/TDT) measurement, they measure signals collected in response

to a transient source. Unfortunately, error correction is difficult to apply directly in the time domain. While modern TDR/TDT systems may provide limited error correction, this is often insufficient to fully compensate for some primary error mechanisms, such as large, closely spaced reflections due to discontinuities at test probes and connectors.

A time domain network analyzer (TDNA) is a good match between the needs and resources of the packaging industry since it measures frequency-dependent network parameters using a transient source. TDNA (also an abbreviation for “time domain network analysis”) can be inexpensive while providing accuracy sufficient for purposes, including electronic packaging and interconnection characterization. However, like a frequency domain network analyzer (FDNA), a TDNA requires calibration to remove the effects of cables and connectors, nonideal source and sampler response, and source and sampler mismatch.

The accessibility and low cost of the instrumentation have helped boost interest in TDNA. Another important factor is the potential for high performance. This is best illustrated by recent work establishing its feasibility for on-wafer measurements at frequencies up to several hundred gigahertz [2,3]. Furthermore, since TDR/TDT systems are typically configurable with many channels, multiple-port TDNA is feasible and is desirable for many packaging problems. However, two-port characterization is the standard for FDNA, and most common calibration methods are restricted to a pair of ports. In this paper, we consider only two-port measurements.

Both FDNA and TDNA are technically applicable only to linear devices. However, they can be applied to weakly nonlinear test devices in the small signal regime. With TDNA, great care is required in order to ensure that the device remains linear at all frequencies, for the source may produce large signal amplitudes at frequencies lower than those of interest. Passive electronic packages and interconnections are quite linear and represent an ideal application of TDNA.

While the primary focus of TDNA is to measure frequency-domain network parameters, these can be used to compute transfer functions and thereby error-corrected time-domain responses to any given incident waveform. Resultant error-corrected TDR/TDT methods are described in [4] and [5].

### TDNA System Example

Figure 1 shows a typical TDNA system for microelectronics measurement. A high-speed digital sampling oscilloscope is linked to TDT/TDT sampling heads. These generate approximate voltage step-functions on a terminated 50  $\Omega$  transmission line and sample the total voltage at some nearby point. The line is connected to a microwave wafer probe by a short length of coaxial cable. The probes, mounted in a wafer probe station, are used to contact test pads at the wafer surface. We used such a system to probe devices in coplanar waveguide transmission lines, described in more detail below.

We contacted both ends of the devices and measured TDR and TDT responses in both directions. Figure 2 shows examples of TDR responses, where the starting time is arbitrarily set to 0. The measurement begins by the rapid closing (or opening) of a switch; this suddenly imposes a dc voltage onto a transmission line. No signal appears at the receiver prior to some later time (around 0.5 ns in the figures), at which the step-like incident signal arrives. The signal propagates through the coaxial cable and probe with only small reflections in the transmission system. However, the signal may encounter a large reflection at the end of the probe, depending on the contacted device. Until the time at which the signal from the probe tip is first returned to the sampler (roughly twice the one-way time of flight), the signal is independent of the test device.

Figure 3 shows the corresponding TDT signals. The signal arrives at a receiver only after transmission through the test device and through both sets of cables and probes.

### Errors in Need of Correction

The test fixture or probe, including cables and connectors, in which the microelectronic test structure is to be measured is the most apparent source of measurement error. The probe can be modeled as a pair of two-port error networks, one attached to each port of the device under test. Historically, time domain methods may attempt to account for these fixtures in terms of their transmission parameters alone. However, as shown in Fig. 2, reflections inevitably occur at fixture or probe contacts; the resulting errors can have disastrous implications in the frequency domain. Due to the existence of closely spaced multiple reflections, simple “gating” of the signal will

not suffice.

FDNA users are well aware of these problems and have developed numerous calibration schemes to correct for them. Much of the additional systematic error in both FDNA and TDNA can be modeled by including both it and the physical test fixture in an “effective test fixture.” The additional “switching” and “isolation” errors that are typically corrected in FDNAs are essentially absent from most TDNA systems.

FDNA normally uses a directional coupler which samples the incident signal to gather a reference. TDNA lacks such directionality, since only a single sampler must account for both incident and reflected signals. However, in principle, we need not sample the incident reference signal; it is irrelevant as long as the test devices are linear and the signal at a given frequency is well above the noise floor. In this case, any imperfections in the source (and the sampler as well) can be lumped in with those of the test fixture. However, this presumes that the source, although unknown, is completely repeatable. Unfortunately, in many TDR/TDT instruments not specifically designed for TDNA, the time at which the incident step is generated is not carefully controlled. The effect on frequency-domain results can be devastating.

Several solutions to the problem of incident-step drift are possible. One method, incorporated in [2] and [3], is to synchronize the source and receiver to virtually eliminate jitter as well as time-base drift. Another is to correct the time offsets by inspecting the arrival times of the incident step of the various device measurements. This approach was taken in [6] and [7]; the latter demonstrates that the procedure can work well. However, external correction limits the opportunity to apply waveform averaging for noise reduction, since drift that occurs during the averaging process is impossible to correct. An improved approach, which was used in the work discussed below, is to integrate a form of this correction method directly into the instrument to obtain closed-loop, real-time error correction of each waveform in the average [8].

### Calibration

Until recently, only partial error correction methods were used to improve the quality of measured TDNA data. In the past few years, more complete calibration techniques, similar to those developed for use with a conventional FDNA, have been applied to TDNAs [4,5,6,7,9,10,11]. Nearly all of these are based on lumped-element standards, which are inherently inaccurate at high frequencies. While the accuracy may be sufficient in some cases, critical and broadband applications demand an alternative procedure. Therefore, [7] makes use of the multiline TRL method [12], which, without fully charac-

terized standards, provides an accurate and well-characterized calibration that is suitable as a benchmark reference [13]. The multiline version permits calibration over a wide frequency band, which is necessary for an accurate calibrated time domain representation, and uses redundancy for the suppression of random error. The method also properly accounts for the frequency-dependent characteristic impedance  $Z_0$  of the transmission lines, using the technique of [14]. Since this method provides not only a complete calibration but also a full characterization of the transmission lines, it is useful in the study of packaging interconnections [15].

### Measurements

In order to illustrate the potential of TDNA, we applied it using a typical laboratory oscilloscope and compared the results to those of a high-quality commercial FDNA. We used the multiline TRL calibration in both cases.

The multiline TRL standards were constructed of coplanar waveguide on GaAs [16]; the gold center conductor was 73  $\mu\text{m}$  wide and separated from the ground plane by 49  $\mu\text{m}$  gaps. The six line standards included a 0.55 mm through-line and five additional lines that were 2.135, 3.2, 6.565, 19.695, and 40 mm longer. These were measured using on-wafer probes and a commercial digital sampling oscilloscope (DSO) fitted with two 20 GHz TDR sampling heads. For each standard, we collected 4096-point TDR and TDT records (using an increment of 2 ns) with the stimulus on port 1 and then repeated the process with the incident signal on port 2. We applied extensive signal averaging (using 1024 waveforms) to improve the signal/noise ratio, and we applied an internal closed-loop time-base drift correction [8] in the DSO. Unknown devices were probed in the same fashion as the standards. After appropriate preprocessing, each waveform was subjected to a fast Fourier transform (FFT) that was modified to account for the step-like nature of the waveform [17]. The raw FFTs, considered as uncorrected scattering parameters, were used as input into the frequency-domain multiline TRL calibration program.

Figure 4 displays the relative phase velocity (normalized by the free-space speed of light  $c$ ) of the transmission lines. The TDNA and FDNA results are similar. Above 5 GHz, signals propagate with little dispersion but at a speed much less than  $c$  due to the GaAs substrate. However, the phase velocity drops dramatically at the low frequencies due to field penetration into the gold conductors [1].

Figure 5 shows the measured attenuation per unit length. The TDNA and FDNA results are similar to well above 10 GHz.

Figures 6 and 7 show the good quality of the TDNA characteristic impedance measurements. The low-frequency behavior is again due to metal loss [1]. In order to obtain this measurement, we used the method of [14], which required an evaluation of the capacitance per unit length of the line. We obtained this capacitance using the methods of [18] performed with an FDNA; a TDNA could also be used.

For a better understanding of this behavior, we can observe the transmission line equivalent circuit parameters [19]. In particular, Fig. 8 shows the inductance per unit length, which is essentially flat at high frequencies but grows below 5 GHz as the internal inductance of the metals comes into play. For a detailed description of the low-frequency transmission line behavior, see [1].

Measurements of  $Z_0$ , while useful in understanding the transmission line, are also critical in constructing network parameters, since  $Z_0$  is the initial reference impedance of the TRL calibration [19]. Scattering parameters of the 40 mm transmission line are shown in Figs. 9 and 10. Figure 11 shows the real part of the measured load impedance of a small resistor embedded at the end of a length of coplanar waveguide.

### Discussion

Based on the results presented here, time-domain network analysis does not appear to be as accurate as conventional frequency-domain network analysis. However, TDNA is more than accurate enough for purposes such as characterizing packaging and interconnections. For those purposes, users will make the choice based on cost, convenience, and availability of instrumentation.

Another way to judge the success of the method is to compare it to uncorrected measurements, either in the time or the frequency domain. In other words, given a DSO, how do we make the best use of it? Although we have not illustrated it here, the sorts of measurements we performed would be meaningless without some error correction. We showed the multiline TRL calibration to be effective for TDNA. Alternative calibration methods are possible and deserve to be compared in detail.

As we noted earlier, other instrument configurations are also possible. Alternate TDNA systems may be competitive with FDNA on performance. Noteworthy in this regard are [2] and [3], which exceed the frequency bounds of existing FDNA systems.

### Conclusion

Time domain network analysis is beginning to emerge as a practical tool, particularly for the characterization of microelectronics packaging and interconnec-

tions. As the packaging industry is confronted with more strenuous electrical design requirements, TDNA will take its place as a basic engineering tool.

### Acknowledgements

Tektronix, Inc. contributed instruments and support for this work as part of a Cooperative Research and Development Agreement with NIST. Stan Kaveckis Tektronix supported the project and critically read the manuscript. Leonard Hayden of NIST, with the assistance of John Rettig and Dmitry Smolyansky of Tektronix, helped develop the TDNA data acquisition software used here.

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